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Free-electron laser operation with a superconducting radio-frequency photoinjector at ELBE

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ABSTRACT

At the radiation source ELBE a superconducting radio-frequency photoinjector (SRF gun) was developed and put into operation. Since 2010 the gun has delivered beam into the ELBE linac. A new driver laser with 13 MHz pulse repetition rate allows now to operate the free-electron lasers (FELs) with the SRF gun. This paper reports on the first lasing experiment with the far-infrared FEL at ELBE, describes the hardware, the electron beam parameters and the measurement of the FEL infrared radiation output.

1. Introduction

High-brightness electron sources for CW operation with megahertz pulse repetition rates and bunch charges up to 1 nC are still a topic for research and development. One promising approach is a superconducting radio-frequency photoelectron injector (SRF gun). Similar in the basic design to a traditional RF photoelectron injector, the SRF gun has a superconducting niobium cavity instead of a copper RF cavity. Therefore the SRF gun can combine the high brightness of normal conducting RF photo guns with the advantages of superconducting RF, i.e. low RF losses and CW operation. Proposed by Chaloupka and co-workers [1] in 1988, the first experimental set-up was installed at the University of Wuppertal [2]. Later, the first electron beam from an SRF gun with a half-cell 1.3 GHz cavity was produced at FZR (now HZDR) by Janssen and co-workers [3] in 2002. The work has been continued by developing and commissioning a 3½-cell SRF gun for the ELBE accelerator [4]. At present, SRF gun research and development programs are conducted in a growing number of institutes and companies like AES, Peking University, BNL, DESY, HZB, HZDR, Niowave, NPS, TJNAF, and Wisconsin University. (Ref. [5] gives a detailed overview.) Several recently launched accelerator-based light source projects plan the application of SRF guns [6–8].

The radiation source Electron Linac of high Brilliance and low Emittance (ELBE) at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) is a user facility and operates two infrared free-electron lasers (FELs) for several years now [9–11]. The undulators of the two FELs have period lengths of 27.3 mm (U27), and 100 mm (U100) respectively and produce radiation in the wavelength range between 4 and 250 μm. The distinctive feature of ELBE is its continuous wave (CW) operation. Fitting them to the optical resonator lengths of the FELs of 11.53 m, electron bunches with a repetition rate of 13 MHz can be generated within uninterrupted trains. Additionally to the FELs the ELBE electron beam is used to generate various kinds of secondary radiation like gamma rays, positrons, and neutrons. Each of the two main radio-frequency (RF) accelerator modules of the ELBE linac contains two superconducting cavities. The cavities are kept at 2 K using superfluid helium delivered by a helium liquefier. The design of the 9-cell, 1.3 GHz cavities was developed for the TESLA project at DESY [12] and the maximum acceleration field is specified to 10 MV/m giving a maximum total energy of 40 MeV.

Since the commissioning of ELBE, the electron beam has been generated by means of a thermionic electron source with dispenser cathode and pulsing grid. A high-voltage of 235 kV is applied to this gun. Two RF bunchers compress the pulse length of 500 ps at the exit of the source to about 10 ps (FWHM values) at

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the linac′s entrance. Although very reliable for user operation, the source has the disadvantages that the bunch charge is limited to 80 pC, and that the transverse emittance is reaching about 12 mm mrad rms at this bunch charge.

The ELBE SRF gun is able to inject an electron beam into the linac using a dogleg-like connection beamline since 2010 [13]. In 2012 a new ultraviolet (UV) driver laser for the SRF gun was installed which had been developed at the Max-Born-Institut by Will and co-workers [14]. This laser fulfills the specification for the planned user application and is able to deliver pulses with 13 MHz (ELBE FEL mode) as well as lower repetition rates (500, 250, and 100 kHz) for high-charge operation. The new laser allows applying the SRF gun for the FEL operation at ELBE. In this paper we will report on the first successful attempt of this procedure. It is worth to mention that the SRF gun at ELBE is still the only one of this type which delivers beam to an accelerator and furthermore this is the first demonstration of FEL lasing with such a gun at all.

2. SRF gun

A schematic design view of the SRF gun is presented in Fig. 1. The cryomodule contains the superconducting cavity, tuners, helium tank, liquid N_2-vessel with cryogenic shield, magnetic shielding, photocathode with support and cooling system, higher-order-mode couplers, main power coupler, and further diagnostics and auxiliary systems. The 1.3 GHz niobium cavity consists of three TESLA cells [12] and a specially designed half-cell. At the cathode side of the cavity an additional choke cell, also superconducting, prevents the leakage of the RF field of the cavity towards the cathode support system. Details of the SRF gun design have been published in [4].

The normal conducting photocathode is installed in a special support system, which is isolated from the superconducting cavity by a vacuum gap and cooled with liquid nitrogen. This design allows the application of semiconductor photocathodes of high quantum efficiency. Up to now Cs_2Te photo cathodes have been used. This material has both high quantum efficiency (QE) and robustness against vacuum deterioration [15]. One of the SRF gun related questions is how to guarantee the compatibility of the normal conducting cathode and the superconducting cavity. The operation experience is that the photocathodes have lifetimes of months and relatively stable QE [16]. That is at least true for the previous operation conditions of the gun with a typical laser power of 0.5 W, a laser power density of less than 1 W/mm^2, and pulse energies up to 10 μJ. Before the FEL experiment, the gun produced an average current up to 0.5 mA with the same photo cathode and the total charge extracted was 200 As so far.

The second question is whether the photo cathode operation degrades the superconducting cavity over time. Therefore the cavity performance, i.e. the intrinsic quality factor Q_0 versus the peak electric field, has been measured regularly since the commissioning of the gun in 2007. Fig. 2 shows some results of these measurements. The practical limitation for the peak field value of the acceleration field in the present cavity is the Q_0 decrease and the corresponding increase of the RF heat loss in the cavity surface. For higher fields the source is the strong field emission. The acceptable heat loss is about 30 W. From 2007 until 2011 the values for the peak fields were 16 MV/m in CW and 21.5 MV/m for pulsed RF. (3 MeV and 4 MeV kinetic energy, respectively.) A temporary increase was obtained by high power processing (HPP) of the cavity. In autumn 2011 a number of photocathodes were exchanged within a short time for testing new designs and

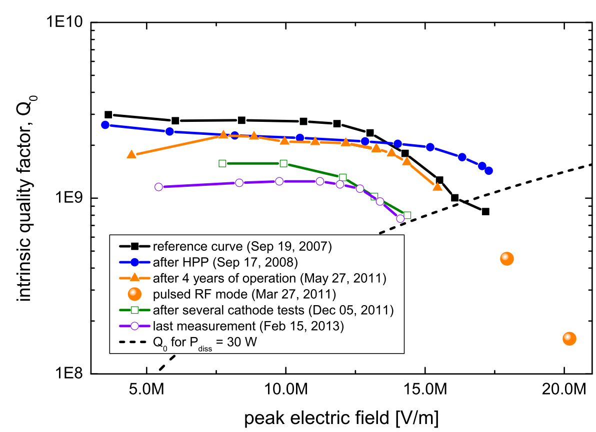

Fig. 2. Measurement of the cavity performance.

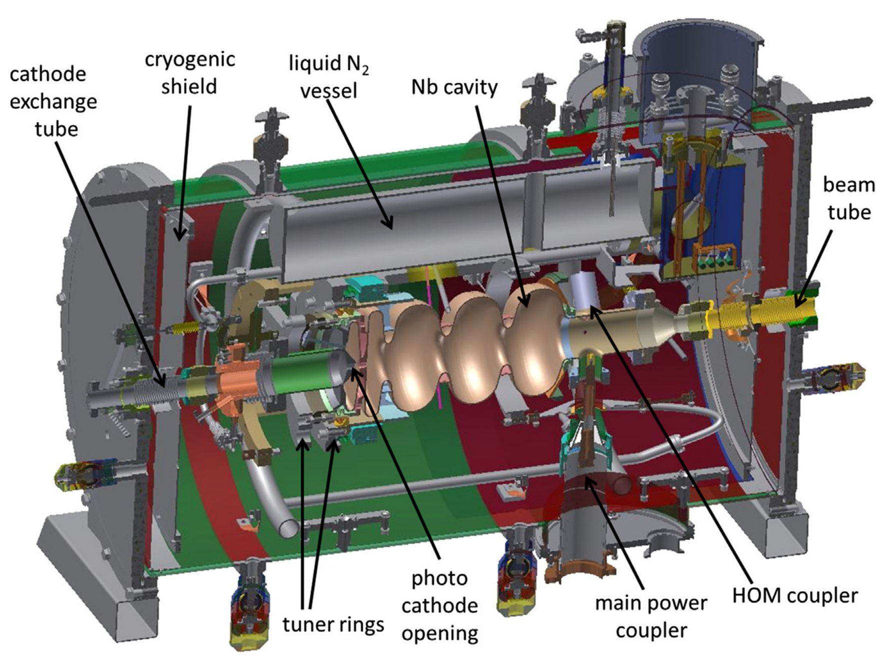

Fig. 1. Cross-section CAD drawing of the 3½-cell SRF gun cryomodule.